Current word count = 2639

- Cover crops reduce weed biomass, but not weed density
- Grass monoculture cover crops offer the most consistent weed suppression
- At least 5 Mg ha^{-1} of cover crop is required to reduce weed biomass 75%
- Producing 5 Mg ha^{-1} of cover crop requires early planting and late spring termination
- Managing cover crops for weed suppression will require changes in policy and agronomy

Cover crops and weed suppression in the US Midwest: A meta-analysis and modeling study

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CC, cover crop; CCBIO, cover crop biomass; Midwest, Midwestern region of the United States, SALUS, System Approach to Land Use Sustainability; WBIO, weed biomass; WDEN, weed density

ABSTRACT

In addition to soil health and conservation benefits, cover crops (CCs) may offer weed control in the Midwestern United States (Midwest), but individual studies report varying effects. We conducted a meta-analysis of studies measuring weed biomass (WBIO) or density (WDEN) in paired CC and no-cover treatments in corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr) rotations in the Midwest. Fifteen studies provided 123 paired comparisons of WBIO and 119 of WDEN. Only grass CCs significantly reduced WBIO, while no CC reduced WDEN. We found no evidence CC management factors (e.g. termination method) directly impacted outcomes. Our dataset showed a 75% reduction in WBIO requires at least 5 Mg ha^{-1} of CC. Simulations from a process-based model (SALUS) indicated achieving 5 Mg ha^{-1} requires substantially earlier fall planting and later spring termination in most years, conflicting with typical cash-crop planting and harvesting. We conclude CCs significantly reduce WBIO, but current CC management constraints render these reductions variable and uncertain.

INTRODUCTION

Winter annual cover crops (CCs) have been heavily promoted in the Midwestern ‘Corn Belt’ region of the United States (Midwest) due to an increasing need for practices that enhance soil health and water quality. Despite clear environmental benefits (Daryanto et al., 2018; Kaspar and Singer, 2011), less than 10% of Midwestern cropland is currently managed with CCs (Seifert et al., 2018). The lack of short-term economic returns from growing CCs overwhelms long-term environmental benefits, creating a major barrier to wide adoption (Plastina et al., 2018; Roesch-Mcnally et al., 2018). If CCs can reduce weed management costs, this could provide immediate monetary incentives for adoption. Previous literature syntheses have found CCs reduce weed pressure across various cropping systems, but the direction and magnitude of effects are context-specific (Osipitan et al., 2018). Given its ubiquity and significance in the Midwest, the corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr) production system merits explicit examination. Unfavorable fall/winter climatic conditions in the Midwest are known to limit CC establishment and growth (Baker and Griffis, 2009; Strock et al., 2004), which in turn may affect factors governing CC performance relative to weed management. Region-specific analyses can also provide more precise CC biomass (CCBIO) production targets for weed suppression (Baraibar et al., 2018; Mirsky et al., 2013) and explore how planting or termination timing affects the feasibility of achieving those targets.

To address these gaps, we synthesized data from published field studies measuring weed responses to CCs in corn-soybean systems in the Midwest. Our objectives were to (1) quantify how environmental conditions and management practices affect weed responses to CCs, (2) identify Midwest-specific CCBIO targets for providing significant weed suppression; and (3) evaluate the feasibility of achieving these targets under different CC planting/termination scenarios.

METHODS

Meta-analysis of weed-responses to cover crops

We conducted a systematic search of literature using ISI Web of Knowledge (WoS, available online) Core Collection and CAB Direct databases. Search details are in supplementary text, including a PRISMA diagram and list of included publications (S1). In our database, we included weed biomass (WBIO), weed density (WDEN), and cash-crop yield as response variables. We recorded values in a paired format, requiring each pair of response variables to be measured in the same crop at the same time with all aspects of management held constant except for a treatment of a fall-planted CC. Ancillary data included geographical location, climate, and soil characteristics of the study site; cash-crop and CC management including species, tillage system, planting and termination methods and dates; and experimental information such as timing of weed measurements and type of weed (S1). The complete database is published and available on Iowa State University's DataShare platform (Nichols et al., 2020).

All data manipulation and statistical modelling were done in R version 3.6.1 (R Core Team) using the *tidyverse* meta-package (Wickham et al., 2019) and others (Grolemund and Wickham, 2011; Firke, 2019). A detailed account of statistical methods is presented in supplementary material (S2), and all R code is available on github at (https://github.com/vanichols/ccweedmeta-analysis). In brief, all statistical models used the log-transformed response ratio (measurement in the CC-treatment over measurement in the no-cover treatment) as the response variable (Gurevitch et al., 2018). Mixed-effect models were used with the modifier of interest as a fixed effect and a random intercept for each study using non-parametric weighting based on the number of replicates (Adams et al., 1997). All linear models were fit using the *lme4* package (Bates et al., 2015), and results were analyzed using *lmerTest* (Kuznetsova et al., 2017) and *emmeans* (Lenth et al., 2018). Means and 95% confidence intervals were back-transformed for reporting purposes. To identify suites of practices predictive of achieving both a reduction in weeds and an increase in cash-crop yield with CCs, we fit random forest models (Kuhn and Johnson, 2013) using several R packages (Hothorn et al., 2006). All statistical results are in supplementary materials (S3).

Simulation of cover crop biomass

To investigate the feasibility of growing CCs for effective weed control in the Midwest, we used the System Approach to Land Use Sustainability (SALUS) model (Basso and Ritchie, 2015) to simulate winter rye (*Secale cereal* L.) biomass across a range of soils and weather conditions of the Midwest. Rye is the most prevalent CC species used in the Midwest (Singer, 2008) and represents the best choice for maximizing CCBIO production in this region (Appelgate et al., 2017; Ruis et al., 2019). Specific simulation details are provided in supplementary text (S4). Three CC planting dates were explored: 15-Sep (optimistic), 7-Oct (realistic), and 1-Nov (late).

RESULTS

Meta-analysis results

Fifteen articles fit our criteria, producing 123 response ratios for WBIO and 119 response ratios for WDEN (Nichols et al., 2020). The studies include a range of site characteristics and management representative of Midwestern corn-soybean production systems (S1). Overall, CCs significantly reduced WBIO (p=0.02), which was robust against publication bias (>3000 unpublished null-studies needed; Rosenthal, 1979) and the removal of individual studies (p-values ranged from 0.01-0.04). There was no evidence CCs reduced WDEN (p=0.98). Neither WBIO nor WDEN responses were affected by the subsequent cash-crop (corn or soybean), meaning the response of weeds to CCs was not confounded by differences in cash-crop competition with weeds.

The following categorical modifiers had levels with significantly different effects on WBIO (Fig. 1): CC type (after controlling for CCBIO production; grass, non-grass), measurement in reference to cash-crop planting (before, after), and weed growth habit (winter annual, summer annual, perennial). WDEN had no significant modifiers. For WBIO, grass monoculture CCs reduced WBIO by 68% (CI:41-82%) compared to a non-significant reduction of 33% for mixtures and other types of CCs ($p<0.01$; Fig. 1). Measurements taken before cash-crop planting showed a 74% (CI:51-85%) reduction in WBIO, compared to only 44% (CI:12-64%) in measurements taken after planting ($p<0.01$). Winter annual weeds showed the largest reductions (65%; CI:27-83%), followed by summer annuals (47%; CI:10-68%), with perennial weeds being unaffected by CCs.

Weed suppression was significantly affected by CCBIO for both WBIO (p=0.03) and WDEN (p<0.01). We found an estimated 5 Mg ha-1 of CCBIO at termination reduced WBIO by 75% for grass CCs, but only 40% for other CCs (Fig. 1).

The response of WBIO/WDEN to CC did not depend on any other modifiers tested. A full list of non-significant modifiers can be found in supplemental material (S3) and included production system tillage regime; CC planting/termination method; termination-planting gap; study-site latitude, aridity, and soil type.

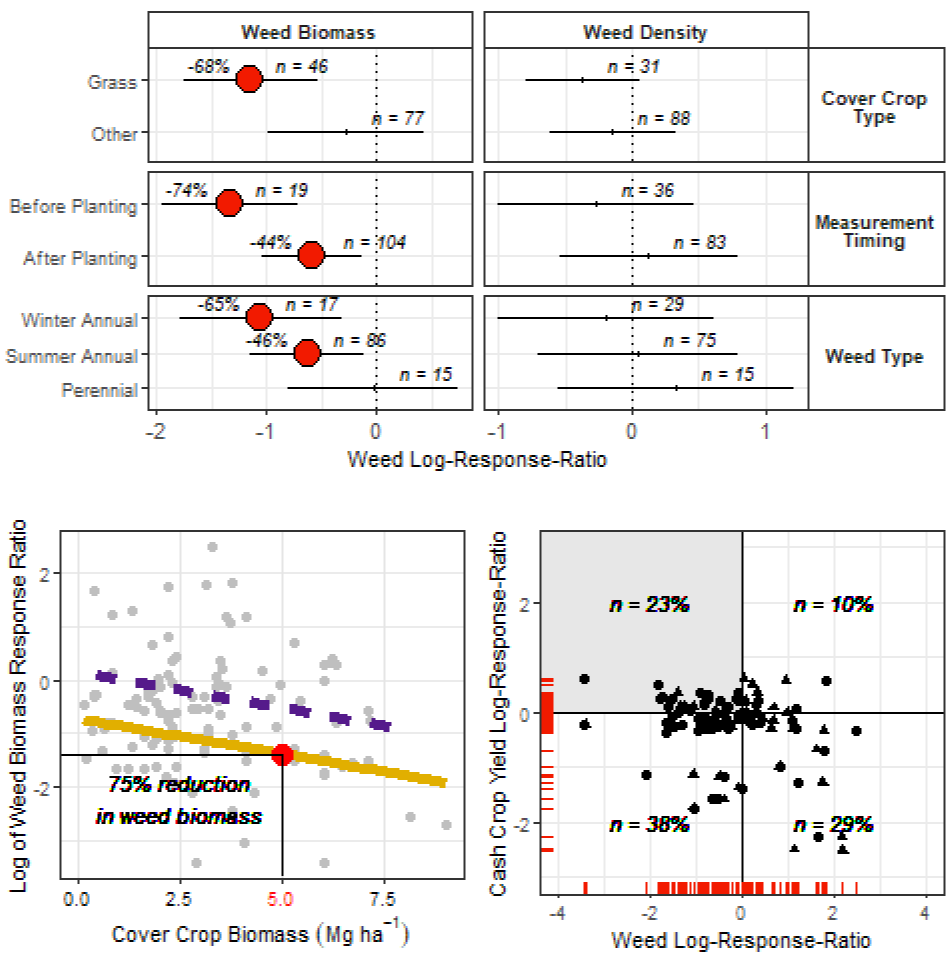


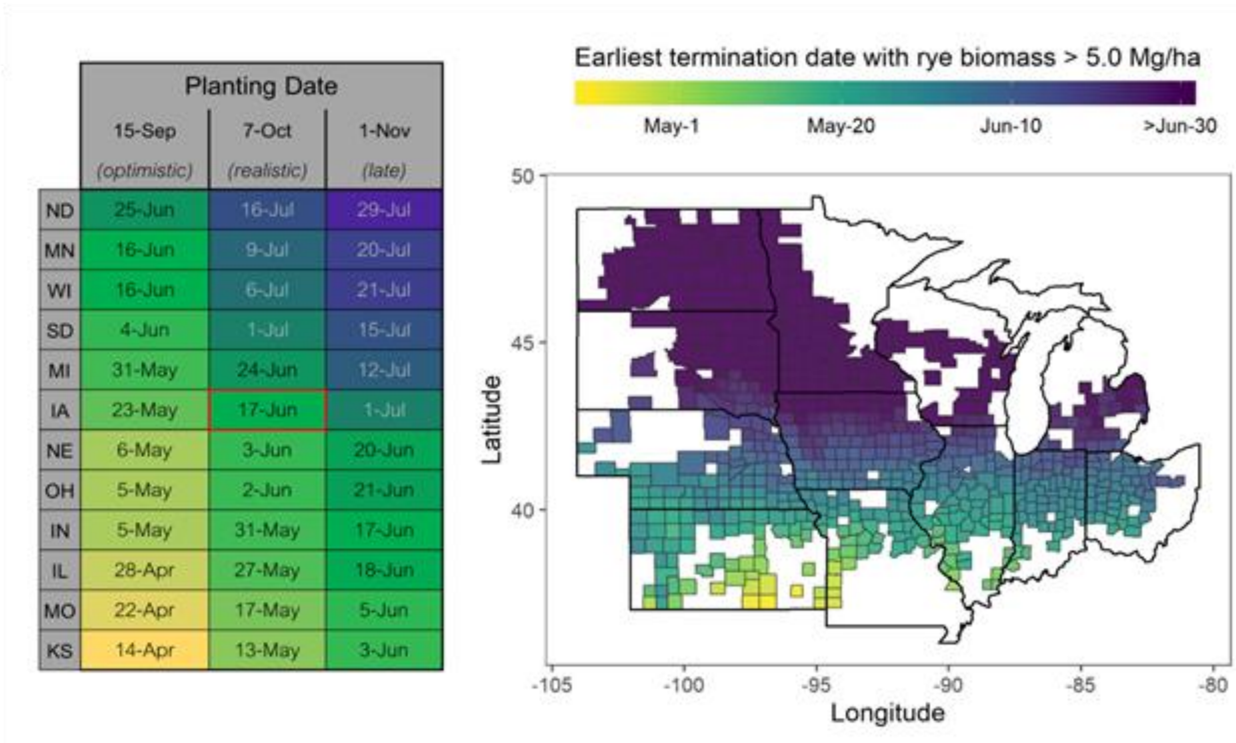
Figure 1 *(Top)* Factors with significantly different effects by level; values less than 0 (dotted vertical line) indicate cover crop reduced weeds, large red points indicate significant effects (p<0.05) with estimates transformed to percent change, n values indicate number of

observations for the estimate, error bars are 95% confidence intervals *(Bottom left)* Linear regressions of weed biomass response to grass (yellow solid line) and other (dotted purple) cover crop biomass production *(Bottom right)* Comparisons where cover crops increased cash-crop yields and reduced weed biomass (circles) or density (triangles) made up 23% of the points (gray quadrant)

In our database only 23% of the comparisons exhibited a ‘win-win’ situation, with a concomitant increase in cash-crop yield and decrease in weed pressure (Fig. 1). Using a random forest model, we found no scenarios that were strong predictors of whether an observation would fall in the win-win category, suggesting maximizing cash-crop yields and weed suppression may not have overlapping CC management strategies.

Simulation model results

For the ‘realistic’ planting date (7-Oct), 2% of counties achieved 5 Mg ha^{-1} by 1-May in ≥ 80% of the weather-years, increasing to only 30% under an ’optimistic’ CC-planting scenario (15-Sep; Fig. 2). With ‘late’ planting (1-Nov), none of the counties reached the threshold by 1-May, and only half did so by 1-Jul. Aggregated on a state-level, Illinois, Missouri, and Kansas were the only states that could consistently achieve 5 Mg ha^{-1} of biomass before typical cash-crop planting dates of early May with ’optimistic’ CC planting dates (Fig. 2).



	Planting Date		
	15-Sep (optimistic)	7-Oct (realistic)	1-Nov (late)
ND	25-Jun	16-Jul	29-Jul
MN	16-Jun	9-Jul	20-Jul
WI	16-Jun	6-Jul	21-Jul
SD	4-Jun	1-Jul	15-Jul
MI	31-May	24-Jun	12-Jul
IA	23-May	17-Jun	1-Jul
NE	6-May	3-Jun	20-Jun
OH	5-May	2-Jun	21-Jun
IN	5-May	31-May	17-Jun
IL	28-Apr	27-May	18-Jun
MO	22-Apr	17-May	5-Jun
KS	14-Apr	13-May	3-Jun

Figure 2. Earliest termination date with rye (*Secale cereal* L.) biomass in excess of 5 Mg ha^{-1} as predicted by the SALUS crop model using 30 years of historical weather for three rye planting date scenarios (15-Sep, 7-Oct, 1-Nov). *(Left)* Results summarized by state at 80% probability levels. In Iowa, for example, rye biomass was greater than 5 Mg ha^{-1} in 80% of the years if planted on 7-Oct and terminated on or after 17-Jun (highlighted in red). *(Right)* Results corresponding to the 7-Oct planting scenario, summarized by county at the 80% probability level.

DISCUSSION

Cover crops affect weeds through interference mechanisms of resource competition and allelopathy (Teasdale and Mohler, 1993), delaying weed germination and development that manifests as lower WBIO. Management that disrupts rather than interferes with weed trajectories, such as crop rotation, may be more effective at reducing WDEN (Weisberger et al., 2019). However, given that reductions in WBIO can increase susceptibility to herbicides

(Wallace et al., 2019) and weed size is directly related to seed output (Thompson et al., 1991), reductions in WDEN may be possible with long-term CC-use. More long-term (> 5 years) work is needed to answer this question.

Monocultures of grass CCs significantly reduced WBIO (by 68%), while other CCs did not (Fig. 1), consistent with recent studies (MacLaren et al., 2019; Smith et al., 2020). Cover-crops interfere with weeds via physical and chemical means, and grasses such as rye may be more effective than legumes and brassicas at both (Creamer et al., 1996; Smith et al., 2020). Furthermore, higher carbon-to-nitrogen ratios of grass CCs (Martinez-Feria et al., 2019; Quemada and Cabrera, 1995) potentially increase residence time of residue and thus suppress weeds longer after CC termination (Ruffo and Bollero, 2003; Teasdale and Mohler, 1993).

While CCs had a stronger effect on weeds before cash-crop planting (Fig. 1), weeds measured after planting are likely of more interest to producers, as they directly represent resource competition with the cash-crop. The stronger reduction in winter annual weeds is not surprising, given the winter growth period of the CC.

The environmental context of the studies had no significant effect on the weed responses nor on CCBIO. This could simply reflect the lack of plot specific information (Eagle et al., 2017; Gerstner et al., 2017), but does suggest environmental context has only an indirect effect on CC-mediated weed suppression.

To prevent an increase in weed seedbanks, reductions in WDEN of 90% (comparable to herbicide effectiveness) are needed (Liebman and Nichols, 2020); our study shows even with 5 Mg ha^{-1} of CCBIO producers are unlikely to achieve this level of weed control, consistent with studies from other areas (Baraibar et al., 2018; Mirsky et al., 2013). Moreover, our SALUS simulations indicate achieving 5 Mg ha^{-1} of rye CCBIO regularly under typical Midwest production scenarios and climates would be challenging (Fig. 2). Even with optimistic CC planting dates (15-Sep), achieving 5 Mg ha^{-1} of CCBIO would require a mid-May or later termination date most years (≥80%) in the majority of counties, well after typical cash-crop planting dates. It should be noted our simulations assumed direct CC seeding with uniform germination (S4) and are therefore not to be extrapolated to other planting methods. While aerial- or inter-seeding can be used to establish CCs into standing crops, these methods are often unreliable (Wilson et al., 2014), and standing crops prevent full sunlight penetration for CC growth well into October. Delayed corn and soybean planting consistently reduces yields (Baum et al., 2019; De Bruin and Pedersen, 2008), and delayed CC termination could be hindered by concerns over crop insurance eligibility (USDA-NRCS, 2019). High CCBIO production could increase other ecosystem services (Blanco-Canqui et al., 2015; Thapa et al., 2018), but may also introduce issues with nitrogen immobilization and CC termination (Whalen et al., 2020). Other studies have examined the effects of CCs on subsequent cash-crop yields (Marcillo and Miguez, 2017), showing no yield benefit from grass CCs. Choosing a CC species to maximize cash-crop yields versus weed suppression may be at odds, and while no-till may amplify yield responses (Marcillo and Miguez 2017) it may not enhance weed control from CCs. The existence of these tradeoffs is supported by the low percentage of observations with a 'win-win' scenario (Fig. 1) in our database.

CONCLUSIONS

Our study, which synthesized work from the 'Corn Belt' region of the US Midwest, shows grass CCs effectively reduce WBIO. We estimated 5 Mg ha^{-1} of grass CCBIO decreases WBIO by 75%, a threshold at which reduction of herbicide-use is possible, but not always advisable. Furthermore, consistently achieving that level of CCBIO in the Midwest may not be feasible within the traditional corn/soybean fallow season. In our dataset, concomitant increases in yields and decreases in weeds with the use of CCs were minimal, highlighting the need to evaluate CC practices using multiple metrics. Therefore, we conclude that although CCs significantly reduce WBIO, which may render other weed management strategies more effective and reduce WDEN in the long-term, current CC management does not consistently suppress weeds. Optimizing CCs for weed suppression will entail both agronomic (e.g. use of different cash-crop maturity groups) and policy (change in insurance structure around CC termination requirements) changes at a broad scale.

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SUPPLEMENTAL MATERIAL

All supplementary information is available in a PDF accompanying this manuscript. The document consists of four sections: (S1) Literature search methodology and results, (S2) Fitting statistical models, (S3) Results from statistical model-fitting, (S4) SALUS model calibration.

DATA AVAILABILITY

All data associated with this analysis has been published (Nichols et al., 2020) and is publicly available at https://iastate.figshare.com/. Additionally, the data is available as an R package on github (https://github.com/vanichols/ccweedmetapkg), and all R code used to analyze the data is available in a github repository (https://github.com/vanichols/ccweedmeta-analysis).

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